Metrological Management of Large-Scale Measuring Systems

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Alessio Carullo

***Abstract*—In this paper, a quality-assurance model is proposed to correctly manage large-scale measuring systems in a sustainable way. Such systems are made up of interconnected hardware devices and software programs that are distributed over a large area and act as single measuring systems. The proposed model is based on a network-assisted calibration procedure, which allows both the hardware and software sections of a large-scale measuring system to be contemporaneously verified. The calibration procedure requires the availability of programmable traveling standards, which are sent to each measuring unit and are remotely controlled through the Internet. Two application examples that refer to the metrological confirmation of distributed measuring systems that monitor the power quality and the environmental pollution are also described.**

***Index Terms*—Environmental factors, interconnected systems, large-scale systems, measurement, quality assurance.**

I. Introduction

THE AVAILABILITY of digital instruments and telecommunication networks allow distributed measuring systems to be arranged at a very low cost. These systems are basically made up of several measuring units, which are interconnected in a data network and are remotely managed by means of a PC. Each measuring unit embeds sensors and acquisition systems and can exploit processing capabilities. If the Internet is employed as the network, a distributed measuring system can cover large geographical areas and is hereafter referred to as a large-scale measuring system (LSMS). This kind of system is the optimal choice for applications that require the measurement of several quantities distributed over a large area to be performed, such as the control of large industrial plants and environmental-pollution monitoring.

Nowadays, the realization of an LSMS is not a technology problem, since single components, such as sensors, instruments, networks and protocols, are commercially available. On the other hand, some problems arise in the metrological management of such systems since the obtained results are the combination of hardware and software processes that take place over a wide distributed environment. The models that are commonly employed for the quality assurance of measuring systems (see the example in [1]) are not suitable for this new scenario. In addition, further problems that are related to the data exchange over the network have to be considered, such as the net latency and the lack of synchronization among units [2]–[4].

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This paper focuses on the metrological confirmation of an LSMS by providing a set of guidelines that are conceived to correctly manage the system in a sustainable and economical way.

II. Architecture of the LSMS

The LSMS is basically made up of several measuring units plus a central PC that are interconnected through a local area network (LAN) or a wide area network (WAN). The central PC remotely configures the units, acquires the corresponding measurements from them and, after some form of processing, makes the final results available to other PCs interconnected in the same network. Different architectures that offer a similar performance can be employed to arrange a measuring unit. A common solution is based on standard or embedded PCs, which interact with the central PC through a network card and with the measuring devices through external [Recommended Standard-232 (RS-232), IEEE-488, universal serial bus (USB), etc.] or internal [industry standard architecture (ISA), peripheral component interconnect (PCI), personal computer memory card international association (PCMCIA), etc.] buses. A second solution employs Ethernet-based I/O devices that allow a measuring unit to be arranged in a very simple way but with very limited processing capabilities. Another possibility consists of employing smart transducers that can be directly interfaced to the network [5]. In any case, the results an LSMS provides are a combination of hardware processes, which usually take place at the measuring unit, and software processes, which are implemented both on the unit PC and on the central PC. Therefore, the LSMS metrological-management model has to involve hardware components as well as software programs, thus implying the following.

1) Involved measuring devices have to be periodically calibrated.
2) Software programs have to be managed within a quality-assurance model (see the example in [6]).

The common calibration approach, which requires the measuring devices to be moved to a calibration laboratory, is not economically sustainable, since an LSMS can embed a lot of measuring devices that are distributed over a large area. Furthermore, during the calibration time, which is rarely lower than a week, the single unit is unavailable, thus making the LSMS not completely operative. This situation can be very frequent if the number of measuring units is very large. Other problems arise in the verification of the software programs that are involved in the measuring process, which could be a very time-consuming activity if it is performed independently of the

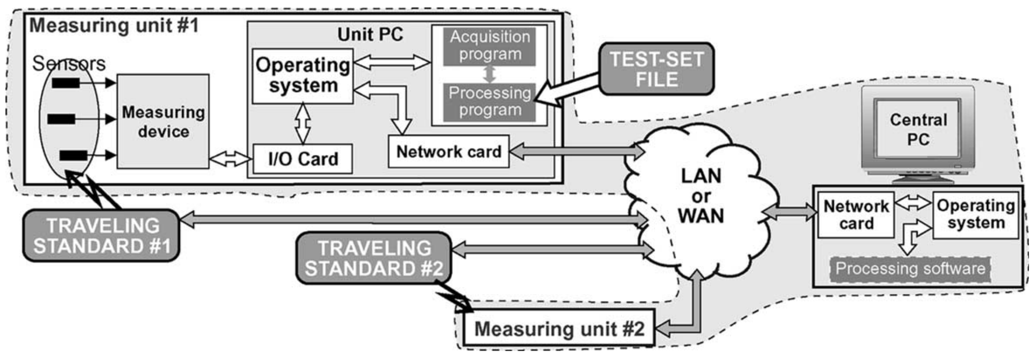

Fig. 1. Example of a distributed functional unit.

device calibration. With the aim of tackling such problems, an on-site calibration solution can be employed, which requires standards and technicians to move to the measuring units. However, such a solution is very expensive and does not completely solve the abovementioned problems. In the next section, an innovative solution is proposed for the metrological management of an LSMS that is conceived to reduce the cost of maintenance of the system and the out-of-service time of the measuring units.

III. Metrological Management of the LSMS: The Proposed Model

The proposed model for the metrological management of LSMSs is based on their intrinsic characteristics: the distributed nature and the presence of an interconnection between the measuring units and central PC. The standalone instrument is replaced with the distributed functional unit (DFU), i.e., the combination of hardware devices and software programs that are distributed over different places and that act as a single measuring system. The DFU inputs are located at one or several units, while the DFU outputs are available at the central PC (see Fig. 1). The hardware section of a DFU embeds measuring devices such as sensors, instruments, and acquisition boards, as well as auxiliary devices, e.g., power supply and conditioning circuitry. The software section includes all the programs that affect the measurement results, e.g., acquisition and processing programs.

The proposed network-assisted procedure is based on traveling standards with network-interfacing capabilities, which are sent to the unit sites and are remotely controlled through the Internet (see Fig. 1). Therefore, the calibration procedure of a DFU is remotely exercised by the central PC, which manages the traveling standards, in order to apply known stimuli at the DFU inputs, configures the involved measuring units, and acquires the corresponding measurements. The traveling standards can be commercially available equipment, e.g., multifunction calibrators and signal generators, or specifically designed devices [7], [8].

A. Confirmation Test Set

The metrological confirmation of a generic measuring system is performed in a group of test points, hereafter referred to as a test set, whose composition determines the effectiveness of the metrological confirmation. Specific guidelines are provided for the test-set choice of some instrument categories, i.e., for digital multimeters [9], while in other cases, the test set has to be designed *ad hoc* by taking several factors into account. Among all the factors that are usually considered, the most important are the nature and range of the measured quantities and the effects of the influence quantities. In the case of a DFU, other factors have to be considered, which are related to the presence of acquisition and processing programs in the measuring path, thus, making the design of the test set a rather tricky problem.

If the DFU output depends almost linearly on n factors and each factor affects the DFU output independently of the other factors, the most efficient choice simply consists in modifying a single factor at a time from its lower level to its upper level. Therefore, such a test set requires to perform $(2 \cdot n)$ experiments. If a nonlinearity behavior is expected with respect to the k of the n considered factors, it is necessary to stimulate the DFU at different levels of the k factors, i.e., if five levels have to be considered for the k factors, the size of the test set will be $[2 \cdot (n-k) + 5 \cdot k]$.

In the presence of interactions among the n factors, the choice of the test set becomes a difficult task: In this case, the design of experiments methodology [10], specifically the factorial design, can be employed for planning the test set. If the number n of considered factors is not high, the full factorial design can be employed, which leads to p^n experiments, with p being the number of levels that each factor assumes. If the DFU output changes linearly with respect to the n factors, two levels are enough for each factor, thus requiring 2^n experiments. This choice allows all single and combined factor effects on the DFU output to be estimated. Usually, a reference test point is defined; then other points are laid out in a symmetrical fashion around the reference center point, thus covering the corners of a hyper cube.

When the linear approximation is not adequate for describing the DFU behavior, the full factorial design is implemented with p number of levels greater than two. If the nonlinearity is related to k of the n factors, a mixed full factorial design is employed, which leads to $[2^{(n-k)} \cdot k^p]$ experiments. However, one should note that the number of experiments could become prohibitive when n and p increase. For example, if $n = 5$ and $p = 3$, 243 experiments have to be performed. In similar situations,

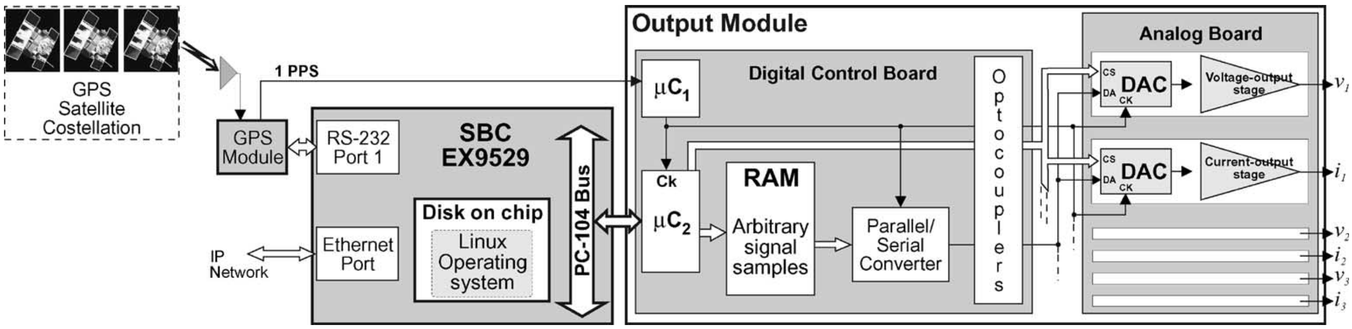

Fig. 2. Block scheme of the GPS-synchronized traveling standard.

the number of experiments can be reduced by means of the fractional factorial design, even though some information could be lost.

When the measuring path of a DFU embeds multiinput algorithms that implement very complex processing, the verification of these software components could require a test set with a very large size, even when a suitable test planning is used. In this case, it is convenient to verify the processing programs separately from the other components by means of a two-step procedure. During the first step, a test-set file is employed to feed the processing program with a large amount of data (see Fig. 1), and the DFU results are acquired at the central PC. In this case, the processing program has to exhibit a software-input port. The second step consists of stimulating the DFU inputs by means of the traveling standards, which are employed to provide the designed experimental test set. Relevant results obtained at the central PC allow the metrological confirmation of hardware devices and acquisition programs to be performed, since the measurements the central PC receives follow a path that includes the software section already verified in the first step.

IV. Application Examples

A. LSMS for Power-Quality Monitoring

The first case study refers to an LSMS that monitors the harmonic pollution in a power system. In this case, different measuring units are distributed over a wide area in order to monitor the critical points of the power system. Each unit typically embeds current transducers and voltage transformers, which convert high currents and voltages to small voltage signals. Such signals are acquired and converted into digital samples by means of a data acquisition (DAQ) board that runs on a PC or a single board computer. Eventually, the obtained samples are processed in order to estimate different quantities, such as power, energy, and specific quality indexes, which are sent to the central PC, where the harmonic power flow is estimated and the harmonic sources are localized [11]–[14]. The effectiveness of such estimations often requires a strict synchronization among the different units, which is usually obtained by means of the GPS [11], [12]. In other situations, in which the measured quantities are averaged over long intervals, such a synchronization is not required, provided that the time difference among the average intervals is lower than a limit value [4].

The estimation of the uncertainty contribution due to the net latency or lack of synchronization among units is not straightforward. An example of uncertainty estimation is described in [4], where the quantities of interest are obtained as average over short time intervals. In this case, a difference in the time intervals of few seconds causes a relative uncertainty contribution in the range of 1% to 5% for a time interval in the range of 10 to 1 min. Therefore, such an uncertainty contribution is comparable with other contributions, as those due to transducers and measuring devices.

Therefore, the main peculiarity of these LSMSs is the measuring-unit synchronization, which leads to a specific requirement for their metrological verification: The different units have to be contemporaneously stimulated with synchronized signals. It would also be desirable to stimulate one or more units with time-shifted signals or distorted waveforms so that the robustness of the whole LSMS with respect to the lack-of-synchronization and the effectiveness in localizing the harmonic source could be evaluated.

The proposed network-assisted calibration procedure seems to fit such requirements, even though commercially-available traveling standards are not suitable for the generation of synchronized stimuli. For this reason, a dedicated traveling-standard has been developed [15], which is essentially an arbitrary-signal generator based on an embedded single board computer (SBC), as shown in the block scheme of Fig. 2. The employed SBC (model EX9529) provides a PC/104 connector and embeds a LAN 100/10M interface, which allows the standard to be remotely programmed through the network. The synchronization capability is obtained by means of a commercial GPS module (Tyco Electronics model A1029), which communicates with the SBC through a serial port. The received GPS sentences are processed in order to extract the universal time coordinate (UTC). Such information, together with the 1-pulse/s signal provided by the GPS module, allows the synchronization of different traveling standards to be obtained. Preliminary tests have shown the possibility to synchronize different traveling standards within 1 μs.

The output module of the traveling standard (see Fig. 2) consists of a digital control board and an analog board. The microcontroller μC_1 (Microchip PIC-16F877) on the digital board provides a local time base that is locked to the GPS clock, while μC_2 manages the signal generation and communication with the SBC through the PC/104 bus. The control board also

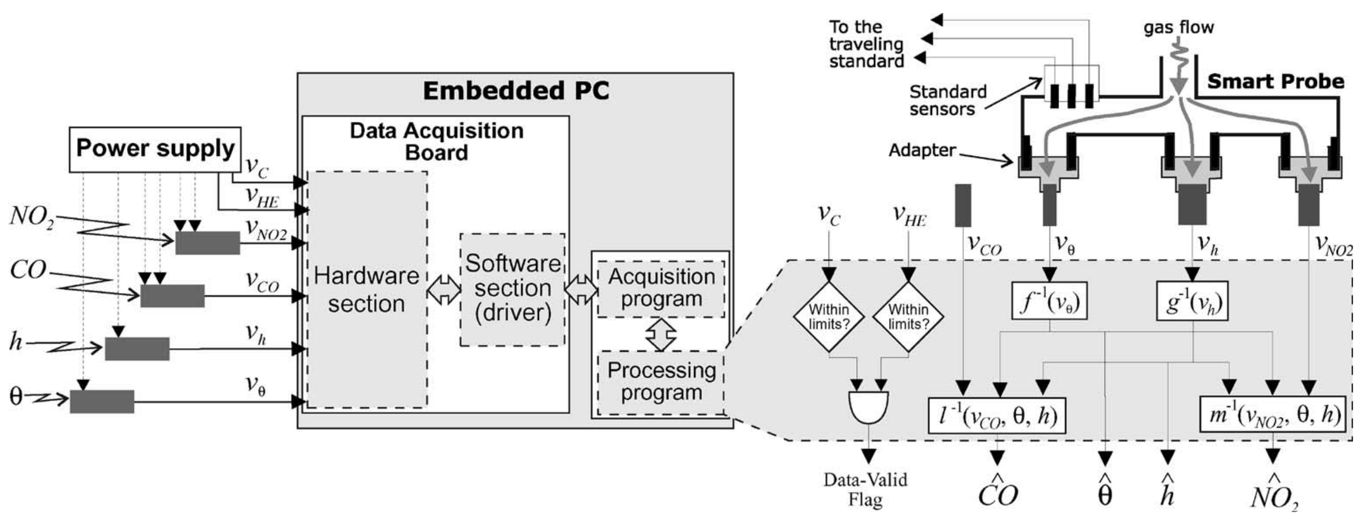

Fig. 3. Architecture of a measuring unit for environmental-pollution monitoring (left-side); processing program and smart probe of the proposed calibrator for gas sensors (right-side).

embeds a RAM, which contains the samples of the signals that have to be generated.

The analog board provides three voltage signals and three current signals. The voltage and current channels employ low-offset and low-drift components and are based on 16-bit digital-to-analog converters (Maxim model MAX542A) that are serially fed by means of the samples that are stored into the RAM. The voltage-output stages are made up of two operational amplifiers (Analog Devices model OP177), which filter and amplify the DAC output, and a final stage that provides a voltage signal in the range of -400 to $+400$ V. The current-output stages employ the same operational amplifier as a filter and a high-current stage in order to provide a current signal that spans in the range of -10 to $+10$ A. The developed prototype provides arbitrary signals with a fundamental frequency of 50 Hz and harmonic components up to 2.5 kHz, i.e., up to the 50th harmonic. More details about the GPS-synchronized traveling standard can be found in [15].

B. *LSMS for Environmental-Pollution Monitoring*

The second case study that is proposed is an LSMS for environmental-pollution monitoring, whose units embed four different devices that sense temperature (θ), relative humidity (h), and concentration of carbon monoxide (CO) and nitrogen dioxide (NO_2), as shown in Fig. 3.

A Zener-diode-based device and a capacitive device that integrates a suitable conditioning circuitry provide the voltage signals v_θ and v_h that change with temperature and relative humidity, respectively, according to known laws. CO and NO_2 sensors are thick-film metal-oxide semiconductor devices, whose resistance depends on the concentration of the target gas that is chemically adsorbed and desorbed on the sensor surface [16]. Such devices require a heater voltage v_{HE} and a circuit voltage v_C and provide the voltage signals v_{CO} and v_{NO_2}. The sensor outputs also depend on the temperature, which affects the chemical reactions, and on the humidity, since the resistance decreases as the water vapor adsorbed on the sensor surface increases.

Sensor outputs and supply voltages are acquired and converted into digital samples by means of a DAQ board that runs on an embedded PC, which processes the obtained samples according to the algorithm that is summarized in Fig. 3. The temperature and relative humidity $\hat{\theta}$ and $\hat{h}$ are estimated by means of the inverse transduction functions of the relevant sensors, while the estimation of the gas concentrations $\hat{\mathrm{CO}}$ and $\hat{\mathrm{NO}}_2$ involve sensor transduction functions and requires a compensation for the temperature and humidity effects to be implemented. The algorithm also checks the voltages v_{HE} and v_C, which have to assume values in a specific range in order to obtain valid results.

A first peculiarity of such an LSMS is the difficulty of stimulating the sensors due to the unavailability of commercial traveling standards that are able to provide the known concentrations of CO and NO_2 . Due to this reason, a DFU that does not include sensors at each measuring unit can be defined. In this situation, the DAQ-board input channels are stimulated by means of voltage signals during the network-assisted calibration procedure, while the sensors that are at the end of their confirmation intervals are replaced with calibrated devices.

With the aim to include the sensors in the DFU, a solution is now under investigation, which consists of specifically designing a traveling standard that allows a known concentration of gas to be obtained. The main difficulty of such a solution is related to the need to expose the sensor under verification to an environment whose composition, temperature, and humidity are known. A further complication is related to the high time constant of the sensors, which implies exposure times to the known environment that in some case could reach tens and even hundreds of seconds.

The proposed calibrator for gas sensors is based on a sealed chamber and a smart probe, which are insulated by means of an electromechanical valve. An approximatively known gas concentration is created in the sealed chamber, and then, the

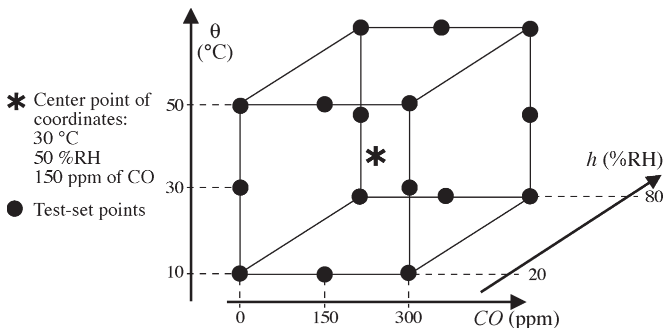

Fig. 4. Test set obtained by means of a fractional factorial design.

electromechanical valve is opened in order to permit the gas flowing towards the smart probe. Such a probe is equipped with standard sensors for temperature, humidity, and gas concentration that provide reference values of such quantities close to the sensor under verification. The sealed chamber embeds a Peltier module that allows the gas temperature to be changed.

Two different methods for creating the gas concentration are under investigation. The first one is based on a continuous flow of air with a known concentration of gas that is contained in a cylinder. This solution does not require particular attention towards the sealing at the probe/sensor interface but requires different cylinders if different gas concentrations have to be created. The second method requires the insertion of a known quantity of gas, e.g., CO, into the sealed chamber by means of a mass-flow controller, so that a known concentration is created by the knowledge of the volume chamber. In this case, only one gas cylinder allows different concentrations to be obtained by incrementing the quantity of gas inserted into the sealed chamber. On the other hand, the interaction with the open air has to be minimized; therefore, suitable sealed adapters have to be used in order to connect the probe to the sensors, as shown in Fig. 3. Furthermore, particular attention has to be paid to the design of the probe, which has to contemporaneously stimulate gas, temperature, and humidity sensors whenever one of the two methods is employed.

Another peculiarity that the present case study exhibits is the multiinput nature of the algorithm that is implemented at each measuring unit. The full factorial design seems to be a good candidate for planning the test set, since strong interactions exist among the input quantities. Furthermore, the estimated concentrations of CO and NO_2 depend on the temperature and humidity according to nonlinear laws [16], thus requiring the controlled factors to assume more than two levels.

The design of the test set for the verification of the $\hat{CO}$ output is considered in the following. The input quantities h, θ, and the concentration of CO are controlled factors, while the heater and circuit voltages v_{HE} and v_C are considered as fixed factors. The influence quantities, mainly the temperature and supply voltage of the DAQ board, are uncontrolled factors, thus requiring some form of experiment replication in order to average their effects. By taking the interactions and the nonlinearity into account, a p^3 full factorial design should be employed. The number p of levels for each factor will be fixed on the basis of the degree of nonlinearity of the DFU output. However, even if only three levels are required, 27 experiments have to be performed without considering replication. Since the control of the considered factors is a difficult task, a fractional factorial design could be employed to reduce the number of experiments. For example, a possible choice for the test set is shown in the cube depicted in Fig. 4, where three levels are considered for the temperature and concentration of CO and only two levels for the relative humidity.

V. Conclusion

The increasing diffusion of distributed measuring systems in different fields has highlighted the difficulty of managing such systems from a metrological point of view. Besides the problem that is faced in the estimation of network-related effects on the measurement uncertainty, the traceability assurance of a distributed measuring system could become a tedious and very expensive activity if performed in the traditional way. For this reason, an innovative approach has been proposed in this paper for the metrological confirmation of a distributed measuring system, with the aim of making such an activity both economically and technically sustainable.

The main advantages that the proposed metrological-management model offers are the possibility to calibrate measuring systems with inputs that are located at different places; a low management cost, since the model implementation does not require the presence of skilled technicians at the measuring units; and the minimization of the out-of-service time of a distributed measuring system.

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